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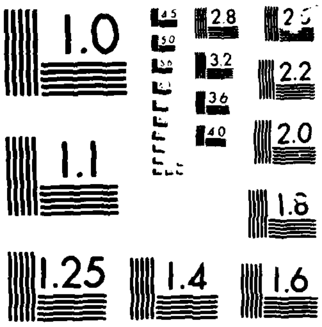

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SURVEY OF RECENT WORK IN RELIABILITY

BY

ANDREW L. RUKHIN

TECHNICAL REPORT NO. 373
APRIL 29, 1986

PREPARED UNDER CONTRACT
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DEPARTMENT OF STATISTICS
STANFORD UNIVERSITY
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1. Introduction

In the present survey we give a review of Soviet studies in reliability theory. Our stress is on the mathematically rigorous theoretical work; to encompass all possible applications seems to be a hopeless task, and this is due not only to the incompetence of this author. Also an attempt was made to put more stress on latest research.

A comprehensive review of the reliability theory are the Handbooks on Reliability by Kozlov and Ushakov (1966), (1975) the first of which has been translated into English (1970). There are also several review papers by Belyayev, Gnedenko and Ushakov (1983), Gnedenko, Kozlov and Ushakov (1969) and by Levin and Ushakov (1965) which are dedicated to the state of art of reliability theory. More mathematically oriented is the monograph of Gnedenko, Belyayev and Solovyev (1965); various aspects of reliability are covered in books by Polovko (1965), Shishonok, Repkin and Barvinski (1964) and Shor (1962). A huge bibliography can be found in Gnedenko (1983).

There is considerable amount of interest on the part of Soviet establishment to reliability questions. All major western monographs on reliability theory have been translated into Russian, and typically are out of sale despite substantial number of edition copies.

In view of the so-called scientific-technological revolution, reliability theory started to develop in sixties when the Soviets began to adopt large-sized and operationally complex technical systems, such as communication systems, fuel-energy complexes, automated control industrial systems, information-computational systems (multi-computer complexes) etc. Unclassified Soviet research in reliability theory seems to be greatly influenced by Western, mainly American, studies. Fundamental notions of reliability theory such as coherent system, distribution with monotone failure rate, optimal maintenance and control, standby items, different types of reserve, etc. found quick response from Soviet applied probabilists already familiar with queuing theory and quality control. The early development of reliability theory had been initiated by B. V. Gnedenko and his collaborators and students (Solovyev, Ushakov, Belyayev, Kovalenko and many others.) It seems, however, that sometimes the results of queuing theory were applied mechanically in reliability problems giving formally correct but practically useless answers.

The weakest point of Soviety reliability research from the authors point of view is the lack of statistical motivation for the mathematical models which allow the evaluation of reliability characteristics. Such models are typically accepted before the system is actually constructed and their reliability is calculated on the basis of the model without checking against real life data on failures.

Still many important results have been obtained by Soviet scholars. Their research however is not always familiar in this country and the present author hopes to bring it to more attention.

The main Soviet research in reliability theory can be found in English translation of the journals "Izvestia Akademii Nauk SSSR, ser Tekhnicheskaya Kibernetika" — "Engineering Cybernetics: Soviet Journal of Computer and System Science", and "Automatyka" — "Soviet Automatic Control".

2. Coherent Systems

In this Section we discuss the problem of determining the reliability of coherent systems introduced by Birnbaum, Esary and Saunders (1961) and developed in Barlow and Proshan (1975). This notion had an enormous impact on Soviet work in reliability, and there is a huge number of papers inspired by this idea.

Consider an arbitrary coherent system formed by n independent components with exponential lifetimes. If the state of the system is described by a binary function $\phi(x)$, and τ denotes the system lifetime, then

$$(1) \qquad P(\tau \leq t) = F(t) = \sum_{x:\phi(x)=0} \prod_{i \in C_0(x)} \exp(-\lambda_i\, t) \prod_{j \in C_1(x)} (1 - \exp(-\lambda_j t))$$

where λ_i is the failure rate of ith component, $C_0(x)$ is the minimal cut set and $C_1(x)$ is the minimal path set. Burtin and Pittel (1972) performed asymptotical study of this formula when $\lambda_i = \bar{\lambda}_i\theta$ with $\theta \to 0$. They showed that if $\Lambda_\theta(t) = F'(t)/(1 - F(t))$ is the system failure rate and r is the size of the smallest cut set, then

$$\Lambda_\theta(t) \sim r\, \theta^r t^{r-1} \sum_{j \in C_1(x)} \bar{\lambda}_j.$$

This formula admits the following interpretation. Asymptotically the failure rate behaves as that of Weibull distribution.

If a structure consists of a large number of components the determination of all minimal path series structures and of all minimal cut parallel structures can be difficult. The knowledge of these substructures is however needed to obtain lower and upper bounds for the reliability, so that it seems rather natural to eliminate minimal path series structures which are formed by large number of components and which have small probability of functioning. Similarly it seems reasonable to exclude minimal cut parallel structures with large number of components and high reliability. In this way, Litvak (1981) has obtained lower and upper bounds for the reliability of a complex system by using smaller sets of minimal path series structures and minimal cut parallel structures which do not have common components. These bounds turn out to be almost exact in many practical situations (for instance, they are exact for a bridge structure). Litvak (1979) and Ushakov and Litvak (1977) have used the mentioned bounds for reliability in the case of other physical characteristics such as capacity, resistance, transportation cost etc. They considered, using methods of graph theory, a two-pole network of an arbitrary structure with given mutually independent estimates of its parameters. As particular cases known Ford-Falkerson

theorem about the maximum flow in a two-pole network and earlier estimates of Esary and Proshan were obtained. Litvak and Ushakov (1984) have also considered different methods to estimate the characteristics of two-terminal networks of arbitrary physical nature. Litvak (1974) has used the technique of Boolean algebras to obtain an exact formula for the reliability of a system represented in parallel-series or series-parallel form.

Lomonosov and Polesski (1971), (1972) considered an information network with n nodes and a set of channels connecting these nodes. Every channel can be in two states, independently of the others: operative (with probability p) and inoperative (with probability $q = 1 - p$). The network failure is defined as the loss of connectivity. They obtained the following two-sided bounds on network reliability R:

$$n(1 - q^{r/2})^{n-1} - (n-1)(1 - q^{r/2})^{n} \leqq R \leqq \sum_{i=1}^{n-1} (1 - q^{v_i}),$$

where r is the number of edges in the smallest cut set, $v_i = |C_i|$, $\{C_i, i = 1, \cdots, n-1\}$ is a collection of cut sets which form the so-called cut basis. The bounds are also sharp in the sense that there are networks of special configuration for which the inequalities turn into equalities. Clearly, replacing p by the channel reliability function $R(t)$ one can obtain useful asymptotic approximations to the network reliability, when, for example, the channels are highly reliable.

Ushakov (1960) considered systems with several possible levels of functioning. The characteristic of quality of functioning is a linear function of reliability of any components, which can be used in optimization problem under maintenance restraints. Netes (1980) used the decomposition method to estimate the level of functioning (effectiveness) of a system. Gadasin (1973) and Gadasin and Lakaev (1978), (1979) have obtained formulae for various characteristics of reliability for a special class of coherent structures (so called recurrent structures). A general study of such structures (like railways or highways, oil or gas pipelines, electrical systems) can be found in the monograph of Gadasin and Ushakov (1975) where a number of new analytic and algorithmic results were obtained. In particular, isotropic systems with a network structure close to that of a planar graph were investigated.

Notice that for complex engineering systems even the notion of failure or reliability is difficult to formulate. A monograph of Dzirkal (1981) is dedicated to methods of assigning the operational efficiency of such systems.

Books of Cherkesov (1974) and Kredenster (1978) deal with so-called systems with time redundancy. Possessing essentially two states "up" or "down" as far as functioning of the structure at a given time moment is concerned, these systems may or may not implement the preassigned task depending on the nature of the whole trajectory of transitions from one state to another. For example, if there is time to carry out an operation then failures of the system during its operation process may require only that one implements once again the whole operation or its part. A similar situation may occur if the system

becomes "inertial" in a sense and allows failure periods not exceeding a given time period. Such systems are most common for information and computational devices where restarting is possible during the operation, and storage (batteries) are available for electronic computers in the event of short-time interruptions of the power supply. The paper of Mikadze (1979) is dedicated to the analysis of reliability of computational systems with time redundancy in the presence of failures and malfunctioning.

Gnedenko (1964a, 1964b) had initiated the study of systems which have an idle backup device which is put into operation as the main device fails. The distribution of failure-free time has been studied under different assumptions. In the case of preventive maintenance Gnedenko and Makhmud (1976) showed that there exists a unique period for preventive maintenance operation which leads to maximal failure-free duration.

Kabashkin (1984) considered systems the behavior of which is described by a stationary Markov process with the graph of state transitions decomposed into two subgraphs. He suggested a method to calculate the stationary probabilities without solving simultaneous equations. Kartashov and Shvedova (1983) offered an approximate method of evaluating the reliability of objects chosen from a control lot in a prescribed way. This method is based on the assumption that changes over time of the parameters of a system can be regarded as a Markov process.

The need to estimate the reliability of highly reliable systems along with the need for simpler tractable formulae resulted in the development of various asymptotic methods. An excellent review of these methods (based mainly on Soviet work) is given by Gertsbakh (1984). For instance, for practical purposes it is important to estimate the difference between the left-hand side and right-hand side of formula (1) (the error of reliability evaluation). Kovalenko (1975) had shown that this difference is bounded by tail probability of Poisson distribution. This fact can be explained by the majorization of the process describing the evolution of the system by Poisson process with parameter $\Sigma\lambda_i$.

Solovyev (1971) introduced a sequence of regenerating processes depending on a parameter which influences the behavior of the process in such a way that the probability of failure during a single regeneration period tends to zero. He obtained interesting theorems concerning the convergence of properly normalized failure time to exponential distribution. Similar results have been obtained by Gnedenko and Solovyev (1974) and (1975) for various models of standby with renewal. Their methods allow estimation of the reliability of complex systems with possible interaction between components. A different method for describing complex systems with renewal is the consolidation of states (see Korolyuk and Turbin (1978)). Beside reducing the dimensionality this method provides a very convenient representation of a complicated semimarkovian process with large number of states by means of a Markov process with smaller number of states.

Kalashnikov (1969) used direct Lyapunov method to estimate the reliability of a redundant system with constant repair time of failed items giving special considerations of

the cases when the number of repair positions is smaller than the total number of items. He obtained some asymptotic estimates of reliability as time increases.

The problems of statistical simulation of functioning of complex systems have been initiated in the USSR by Buslenko (1976), (1978). Reliability aspect of these simulations have been investigated by Gorskiy (1970) and by Groysberg (1981). In particular these authors compared the existing methods of confidence estimation of reliability characteristics (the plane method, the substitution method, the heuristic method) and determined conditions under which each method gives best results. For instance, heuristic method works best for reliability block diagrams of the series type. To increase the efficiency of reliability estimation for redundant systems, where failures are rare, a combined method based on joint use of known procedures was suggested.

Simulations of the operational process of highly reliable systems evoked the need to develop accelerating simulation (Monte-Carlo) methods. Kovalenko (1976), (1980) contributed to this problem by proposing a version of small parameter method for calculation of the characteristics of a Markov chain.

Summing up we see that this branch of reliability theory is very well developed in the USSR with a number of important and original contributions.

3. Systems with Monotone Failure Rate

For many engineering systems, especially for those formed by mechanical components, the reliability characteristics decrease due to the deterioration or "aging" of elements. In the Soviet Union the notion of aging has been introduced by Solovyev (1965), Ushakov (1966), Solovyev and Ushakov (1967). The aging can be formulated in terms of the behavior of the hazard function, namely the conditional probability density of failure given that no failure occurred up to the moment under consideration. For aging elements this function is monotonically nondecreasing. This property of hazard function imposes restrictions on all moments of the distribution which can be used to obtain useful bounds on the whole family of distributions. However, except the mentioned authors there are relatively few Soviet specialists working in this field. There are no reports if a given complex system possesses monotone failure rate. The assumption about exponential distribution of lifetime seems to be too widely accepted.

Ushakov (1966) has constructed the following up upper and lower bounds for the probability P that the system is functioning during a given time period t_0:

$$K(1 - t_0/T) \leq P \leq K\exp(-t_0/T).$$

Here T is the mean time between failures, t is the mean time of regeneration, $K = T/(T + t)$. For small values of t_0 these bounds are close one to another, and for the

evaluation of P in this case it suffices to know only the expected time between the failures, not its distribution.

One of the basic questions of finding the reliability of a system with components whose failure rate is monotone was addressed by Solovyev and Shakhbazov (1981). These authors have obtained lower and upper bounds for the average working time of series and parallel systems formed by aging components with given expected values of life-times.

In the book of Bolotin (1971) some probability models of crossing a certain level by stochastic process were used to describe the failure processes of mechanical parts (see also Konenkov and Ushakov (1975)). A number of mathematical models of failure are considered in the monograph by Gertsbakh and Kordonskiy (1969) which has more references to (rather inaccessible) Soviet papers.

Related subject is the study of accelerated testing. These methods are especially important in the case of elements for which direct verification of reliability under normal working conditions is practically impossible because of a large number of tests needed or for some other technical reasons. A number of different models for accelerated failure processes and corresponding mathematical techniques are given by Perrote, Kartashov and Tsvetayev (1968) and Kartashov (1979).

We mention here also some physical principles suggested as the basics of reliability theory, in particular, controversial Sedyakin's principle (Sedyakin (1966)). The development of such principles (like "heredity" principle or "least action" principle) allows to predict the consumption of a resource and to implement practical models for this consumption. (see Kartashov and Perrote (1968), Perrote and Yavrian (1978)).

4. Optimization Methods of Reliability

Accounting for various restrictions on resources (for instance, cost limitations) results in a number of problems of conditional (linear or non-linear) optimization. As a rule the common features of these problems are the complexity of structural restrictions, large dimensionality and complicated target function. The Soviet research in this field seems to be influenced largely by dynamic programming, optimal inventory problem and queuing theory.

For example, the traditional problems of optimal inventory are treated now as problems of supplying spare parts for complex systems. The supply process has a hierarchical structure and involves a complex rule of replenishing at each stage (see Ushakov (1969), Shura-Bura and Topolskiy (1961), Rubalsky and Ushakov (1975)). These problems are closely related to classical problems of inventory theory when the items are assumed to be withdrawn continuously while the supply is discrete (Rubalsky (1977)). Paramonov and Savvin (1978) examined the problem of determination of an assigned standby for objects on the basis of experimental results. They offered an adaptive method to calculate the

necessary time of service. Dzirkal and Shura-Bura (1980) have suggested a model of functioning of standby units, which was used to obtain a computational scheme to calculate the reliability of the standby group with uncertain reswitching under general assumptions about monitoring of the state of the standby components. Rubalsky (1984) has obtained a procedure which optimizes the standby stock when a part of rejected product is duplicated and a part is repaired.

A study of different maintenance and replacement models is reliability theory of engineering systems has been performed in a series of books by Raykin (1967), (1971), (1978). The optimality of spare parts allocations for electronic devices was studied by Kulback (1970). Lagrange multiplier method has been used by these authors to obtain exact and approximate formulae for the optimal number of spare parts. Under different forms of budget restraints the best allocations of spare parts were found, and some constructive algorithms (essentially of Kettele type) for their practical implementation were suggested. In the case of a problem with a large number of restraints Demin and Malashenko (1974) suggested to use the dual problem of linear programming. In a sense dual to the problem of optimal spare parts allocation with several restraints is the optimization problem of multifunctional systems under one side condition (see also Karshtedt and Kogan (1971)).

Ushakov and Yasenovets (1978) studied two limiting cases. In the first case the functioning time of the system is considerably smaller than the average functioning time of any components, in the second case this time is much larger. Under a budget constraint in the first case one should distribute spare parts uniformly among the components. In the second case if T_i is the average lifetime of the ith unit, the optimal number x_i of spare elements of type i, is approximately equal to

$$x_i \sim t_0/T_i + 1$$

where t_0 is a large fixed number.

Brodetskiy (1978), (1980), (1983) has studied systems with two types of failure (with and without erasing information). To improve the quality of such systems intermediate results are stored in a device that prevents the erasure of data. If a failure leading to the erasure occurred, the process is resumed from the point of last data storage. In this problem it is found that for optimal control of systems operating time, the intermediate results must be stored periodically. These results are extended to the case when the initial task can be interrupted in order to execute another task with higher priority.

Ushakov and Yasenovets (1977) consider a new version of optimal maintenance policy on the basis of limited funds. Assume that the spare items can be obtained until a given sum C_o is spent. During this stage one observes the moments of replacement and the types of failed items. Under resource restrictions an optimization of some functional (like mean time of functioning) is solved by methods of integer programming. One of the methods of integer programming (so-called branch-and-bound method) has been used by Tatashev and Ushakov (1981) to find optimal algorithm of switching standby elements according to a given timetable.

Barzilovich and Kashtanov (1975) consider the problem of optimal preventive replacement when the information concerning reliability is incomplete. The latter circumstance causes drastic complications of mathematical formulation and solution of the problem. Churkin (1984) considered the problem of optimal turning on of a symmetric standby device, when the strategy of turning on and off is such that the length of the queue when the standby device is disconnected is one unit shorter than that at which it is turned on. The optimal procedure was found which takes into account the expenditures associated with turning the standby device on and off, the operation cost and the transition time from one state into another.

The passage times from one state to another by a birth and death process is of interest in reliability theory where the behavior of storage systems with replacements are described by these processes. These times can be interpreted then as the periods of functioning without a failure. Solovyev (1972) obtained the exact distributions for the moment of first crossing. These formulae are rather cumbersome, so the asymptotic distribution of properly normalized first passage moments is shown to be of the form, $1 - ae^{-x}, x > 0,\ 0 < a \leq 1$. The theory of random processes also has been used by Burtin and Pittel (1972b) for joint study of aging and functioning process of an unreliable system. Genis and Ushakov (1983) offered a simple method for optimal choice of the number of standby units in multipurpose systems. They solved the minimization problem of weighted expenditures of resources under a restriction on reliability characteristics and the maximization problem of weighted overall performance under limitations on the expenditure.

Pashkovskiy (1981) has obtained some results concerning engineering diagnostics. In particular, he developed the so-called recursive method which permits the construction of optimal diagnostic procedures for the case of a complex structure of inspection tests and also allows to select a battery of tests out of collection of all possible tests to carry out the inspection.

Related to problems of optimal inventory are problems of dynamic inventory (see Mandel and Raykin (1967), Konev (1974), Ushakov (1981)). In these problems it is assumed that a number of spare items is provided and that these spare items function under lightened conditions so that their failure rate is smaller. It is possible to switch the spare items on into normal working conditions. Clearly the switching on of all items at the beginning causes all of them to begin using up the resource. On the other hand excessively economical switching on of the elements in the first stages of the operation may lead to failure in these stages and to curtailment of further functioning of the system. Thus heuristically there must be an optimal switching on strategy.

Gertsbakh (1966), (1970) studied standby control problems in the situation when the true condition of the system is unknown and can be tested only at given time moments. The number of elements included in the hot reserve after each check-up is selected so as to minimize the probability of system failure during the given operation time. Related problems along with a good list of references can be found in a book of Gertsbakh (1977).

5. Statistical and Mathematical Problems of Reliability Theory

The direction of Soviet work in statistical aspects of reliability theory has been determined by the mentioned book of Gnedenko, Belyayev and Solovyev (1969). The statistical methods used here are mainly confidence intervals of rather complicated parametric function and classical (unbiased or maximum likelihood) estimators of such functions. A study of robustness of these procedures by and large has not been undertaken (although see Chepurin and Dugina (1970)). Methods of applied multivariate analysis or data analysis have not been used in statistical reliability problems.

The work on the confidence intervals has been initiated in Mirnyi and Solovyev (1964) and in Belyayev, Dugina and Chepurin (1967) and was developed further by Pavlov (1982), Sapozhnikov (1971), Sudakov (1974), (1980), Tyoskin (1979). Confidence limits for the reliability have been obtained for different models. Confidence sets for the parameters of monotone failure rate distribution are constructed by Pavlov (1980), who gave conditions under which interval estimates of several unknown parameters can be substituted in the parametric function to be estimated. Interval estimation of the reliability of complex systems by results of reliability testing of its components is a particular case of this problem. The practical importance of these problems is due to the fact that complex systems cannot be accurately tested for their reliability because of constant change in their structure.

Ushakov (1980) and Pavlov and Ushakov (1984) have considered the point estimation problem of reliability and survival function from incomplete observations (truncated or censored). They obtained unbiased estimators in a nonparametric setting for some sampling schemes. A method to estimate quantiles of operation time distribution was suggested. Artamanovskiy and Kordonskiy (1970) considered similar problem, but on the basis of several grouped samples corresponding to simple machine inspection. They have obtained a criterion for the existence and the uniqueness of the maximum likelihood estimator.

Sonkina and Tyoskin (1984) constructed confidence limits for the probability of failure-free operation of a series system with Weibull distribution of the failures. Kaminsky (1984) obtained nonparametric confidence intervals for quantiles of aging distributions with the aim to choose the optimal number of first failures as to maximize the mean value of the lower confidence limit. Related parametric problem was investigated earlier by Paramonov (1975).

Belyayev and Khafid (1984) studied the behavior of the posterior density of reliability parameters. Exponential and Poisson distribution models have been investigated in detail. It was shown that the convergence of the Bayes maximum likelihood estimator to the true parametric value is described by a random process close to a Gaussian one. Different Bayes approach was taken up by Penskaya (1984) who considered an empirical Bayes estimation problem of reliability function when the prior density is unknown but can be estimated on the basis of previous experiments. Groysberg (1980) proposed to use fiducial approach to reliability estimation problem. This approach reduces the problem to that of finding a

distribution function of random arguments with known probability distributions, a solution to which can be obtained by a statistical simulation on a computer.

Various statistical problems arise in processing of data on reliability of items after special experiments or operations. Belyayev (1982) proposed a class of experimental designs for censored data for which one can use methods of sequential analysis. He also suggested the use of Bayesian approach to deal with data on the operation of items with "aging" distribution.

In the textbook of Belyayev and Chepurin (1983) one chapter is devoted to the construction of isotonic estimators of the hazard function which could be used for the analysis of reliability data based on results of shock testing.

Some results on recurrent estimation of reliability from one experiment to another are obtained in Barzilovich (1983). Karapenev (1978) had studied a system with a repair device in which a failure of a component is not detected immediately but after some lag. Under the assumption that the repair time is bigger than the failure rate he obtained an asymptotic estimate of the probability of failure-free time. Statistical aspects of optimal control have been investigated by Rozenblit (1973) under assumption that the model contains unknown parameters. Explicit formulae for estimates of optimal strategies were obtained.

Various estimation methods are compared by Matveyev (1978) in the problem of estimation of failure when the evaluation of the systems parameters can be considered as a Markov process. Lubkov (1980) suggested an algorithm to simulate failures of components of technological systems which can be used to estimate their reliability.

Klebanov (1978) has considered the following characterization problem: Let us consider two systems A and B in series, so that A has n components and B has k components, $n > k$. If the life-time of any of these components is $F(t)$ then the reliabilities of A and B at time t are given by $(1-F(t))^n$ and $(1-F(t))^k$ respectively. Let $T = T(t, F)$ denote the time moment so that the reliability of B at T is equal to the reliability of A at t. What can be said about F if T is given? A characterization of exponential distribution by the property $T(t, F) = at,\ a > 1$ is derived.

Genis (1978) obtained the speed of convergence to an exponential distribution which is the limiting distribution for a random variable with rational Laplace transform. The latter occur in systems with fast servicing, for example, in automatic control systems. Obretnev (1977) characterized exponential distribution in the class of all increasing failure rate distributions by the property $(EX)^2 = \mathrm{Var}(X)$ or $\mu_1 = \mu_2^2$. Azlarov and Volodin (1981) have studied stability of this characterization. They obtained the following estimate which holds for any IFR distribution function $F(x)$

$$sup_{x>0} \mid 1 - F(x) - e^{-x/\mu_1} \mid \leq \left[2(1 - \mu_2/(\mu_1^2))\right]^{1/2}.$$

Various other characterizations of exponential distribution related to lack of memory

property or some other reliability motivated properties were obtained by Klebanov (see Klebanov (1980)).

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

We review the research of Soviet school in reliability theory for the last twenty years. The main subjects under review are complex systems and their reliability, families with monotone failure rate, optimal maintenance and control, and statistical problems of reliability theory (121 refs.).

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